Testing of the Autonomous Microconductivity-Temperature Vehicle and a Direct Technique for the Determination of Turbulent Fluxes with Autonomous Underwater Vehicles

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LONG-TERM GOAL

Our long-term goal is to measure the horizontal variability of heat and salt flux in the upper ocean. This will allow us to study the turbulent boundary layer under nonhomogeneous forcing and the development of coherent boundary layer features such as rolls and Langmuir circulation.

OBJECTIVES

Our immediate objectives are to develop a technique to measure vertical water velocity and the turbulent fluxes of heat and salt with Autonomous Underwater Vehicles (AUV), and to construct a vehicle to fully test and exploit the technique. This has been done in a limited way with our Autonomous Conductivity and Temperature Vehicle (ACTV). Morison and McPhee (1998) use the vertical motion of the ACTV as a proxy for the vertical motion of the water through which it moves. The key elements of the new technique are to use all available vehicle guidance data and account for the dynamics of the vehicle in the estimation of vertical water velocity. A new small AUV called the Autonomous Micro-conductivity and Temperature Vehicle (AMTV) has been built for proving the technique, and test data was gathered at the Surface Heat Balance of the Arctic (SHEBA) station in 1998.

APPROACH

The new technique for determining vertical velocity is based on Kalman filtering (Gelb, 1974). It satisfies the requirements of incorporating all possible sensor data and accounting for vehicle dynamics. The Kalman filter makes an estimate of the state of a dynamic system that is an optimal combination of the modeled response of the system and instantaneous measurements of the system state. The estimates are optimum in a weighted least square sense, with the weighting dependent on the estimated measurement error and forcing variance. The filter is recursive, i.e. the estimates depend only on present measurements and the estimate at a preceding time. As such, a filter only runs forward in time and can indeed be used in real time. The analysis of vehicle data can be done after all data are collected. In such a case the highest accuracy is obtained by running a Kalman filter forward and backward in time over the data in a process called Kalman smoothing.

The first issue in developing the smoothing technique is deriving a system model. The second issue is estimating the measurement errors and the forcing variance. The derived model and error estimates are then used in the Kalman smoothing technique to estimate vertical water velocity. These can be combined with vehicle measurements of temperature and salinity to determine heat and salt fluxes.

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The new technique was first developed using existing ACTV data and has now been applied to data from the new AMTV. The AMTV was designed to take full advantage of the new analysis technique. It is based on the Woods Hole Oceanographic Institution's REMotely operated Underwater measurement System (REMUS). Micro-conductivity and micro-temperature sensors are added for heat and salt flux determination. Test runs in local waters are used to verify the new vehicle model used in the smoothing procedure. Test runs under Arctic ice at SHEBA are combined with simultaneous measurements of turbulence with fixed sensors to test the Kalman results and provide a unique view of turbulence in a nonhomogeneous boundary layer.

WORK COMPLETED

Over the past year this grant has supported a graduate student, Daniel Hayes, to complete development of the Kalman smoothing method and begin testing it with the SHEBA data. Previously, the technique was developed and tested on ACTV data gathered during the 1992 LeadEx program. During the past year the method was also applied to ACTV data gathered at the ANZFLUX station in the Weddell Sea in 1994. This gave us the opportunity to test the method in a boundary layer environment different from LeadEx.

The ultimate test of the Kalman smoothing method required operation of the AMTV in a natural planetary boundary layer in the presence of reliable fixed-point turbulence measurements. This was done by taking the AMTV to the SHEBA ice station in July and August 1998. There we operated the AMTV under various ice conditions in and around leads of various sizes. The runs were initiated from a point adjacent to a portable turbulence mast belonging to Miles McPhee. The mast provided fixed point measurements of turbulent velocity, temperature, and conductivity at one or two depths. These provide data for comparison to the AMTV measurements.

Hayes' work during the past year has been devoted to perfecting the AMTV Kalman smoother and evaluating its performance in the summer mixed layer of SHEBA. The Kalman smoother results from the AMTV are better than from the ACTV even when the same suite of vehicle sensors is used. This is due to the superior accuracy and resolution of the AMTV sensors and in spite of the fact that the AMTV does not follow the water motion as closely as the ACTV. The AMTV results can be improved even further by utilizing its other advanced motion sensors. The AMTV is equipped with a pitch, yaw, and roll rate sensors as well as precision accelerometers. By including data from the pitch rate sensor in the Kalman smoother, Hayes has been able to increase the wave number bandwidth of the velocity estimates from the AMTV data. Comparisons with turbulence measurements from fixed sensors at SHEBA demonstrate the system produces high quality estimates of turbulent vertical velocity and heat flux, and these reveal the importance of horizontal variability in the behavior of the summer under-ice mixed layer. Hayes has prepared a draft paper describing the Kalman smoother technique applied to AUV observations. This was recently presented to the University of Washington in completing the requirements for his Masters degree and gaining approval for continuing pursuit of his Ph.D. We intend to submit the paper to the *Journal of Atmospheric and Oceanic Technology*.

RESULTS

The AMTV data quality from SHEBA is good. We have evaluated some irregularity in the transfer function of the signal conditioning circuits through bench testing and have corrected for it in our signal processing. The micro-temperature and conductivity sensors tend to drift and routinely have to be calibrated against fixed sensors. This has been done for the micro-temperature data and is being done for the micro-conductivity. The AMTV sonar altimeter data are excellent, giving a high resolution of ice draft with virtually no noise. This has made it easy to see the relation between changes in temperature and salinity structure and ice conditions.

Spectra of vertical velocity estimated from the AMTV with the Kalman smoothing technique compare favorably with vertical velocity measured directly with Miles McPhee's Turbulence Instrument Cluster (TIC). The TIC was at 5-m depth at the edge of a large lead. Velocities are estimated using in one case vehicle depth and pitch, and in another case vehicle depth, pitch and pitch rate. The spectra of velocity derived using only vehicle depth and pitch roll off at 0.03 cpm (wavelength 3 m) while the spectra for velocity derived with addition of pitch rate show agreement with the fixed sensor data out to 0.5 cpm (wavelength 2 m). These cutoff wave numbers are impressive because they correspond to a wavelengths approaching the minimum theoretical cutoff wavelength corresponding to the length of the vehicle (1.6 m). All spectra show approximate agreement with the $k^{-5/3}$ spectral slope characteristic of turbulence.

Figure 1 illustrates the importance of the type of measurements made possible with the Kalman smoothing technique. It shows ice draft, vertical water velocity, w', temperature fluctuation, T', salinity fluctuation, S', heat flux, $Q_h = \rho C_p w'T'$, and salt flux, $F_s = \rho w'S'$, measured with the AMTV under a summer lead and adjacent ice. This run was made at SHEBA during a wind event that moved the ice at 15 cm s^{-1} and mixed

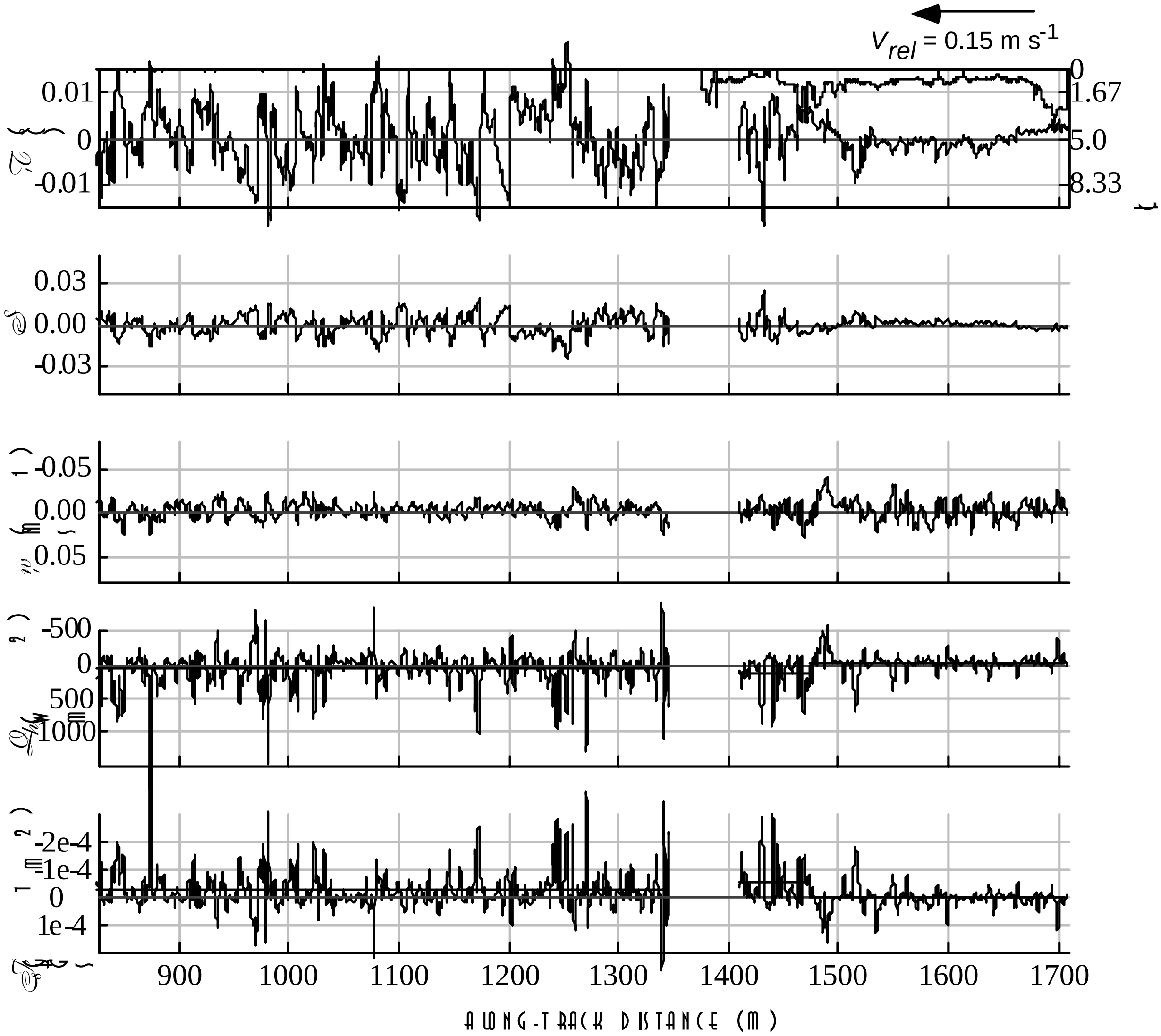

Figure 1. Ice draft, vertical water velocity, w', temperature fluctuation, T', salinity fluctuation, S', heat flux, $Q_h = \rho C_p w'T'$, and salt flux, $F_S = \rho w'S'$, measured during one run of the AMTV under a summer lead and adjacent ice at the SHEBA lead site, August 7, 1998.

fresh water near the surface down into the mixed layer. The average heat flux for the segments (indicated by thick gray lines) under the lead and 200 m downstream is high, 108 W m^{-2}, and the average salt flux is -2.9 kg s^{-1} m^{-2} (negative salt flux implies fresh water mixed downward). These agree with the fixed mast data at the downstream edge. Beyond approximately 100 m downstream of the ice edge, the character of the vehicle measurements changes completely. The average heat and salt fluxes are much smaller, 3 W m^{-2} and 4.1x10^{-6} kg s^{-1} m^{-2} respectively. The temperature and salinity variations are decreased and the vertical velocity fluctuations are increased. Our hypothesis is that the transition at 100m downstream from the ice edge occurs where the vehicle travels from the under-lead boundary layer dominated by freshwater flux and radiative heat input, to the growing, more nearly neutral, under-ice boundary layer under the ice. The unexpected element is the enhanced turbulence at the boundary between the two regimes. This may be due to mixing by underice roughness, or it may be enhanced by instability due to cooler, more saline water being dragged by the ice over warmer fresher water from under the lead. The latter possibility is a new concept that may dramatically affect our understanding of the boundary layer under nonhomogeneous forcing. It suggests that simply taking an areal average of buoyancy flux may overestimate the actual stabilizing effect of nonhomogeneous surface heating and fresh water flux.

IMPACT/APPLICATION

The fundamental impact of this research will be to provide a technique whereby nearly any AUV can provide turbulence data as a side benefit to other sampling it carries out. This is because the proposed technique requires only data from a vehicle's on board motion sensors. Used with simple vehicles, the technique will yield spatial maps of turbulent energy. Used with sophisticated AUVs, the technique will also yield spatial maps of vertical fluxes of the other variables being measured. Such maps will be the key to identifying dynamically critical areas of the Autonomous Ocean Sampling Networks (AOSN) sampling regions and will be crucial to determining the budgets of heat, salt, biomass and pollutants.

TRANSITIONS

Vehicles like the AMTV and the analysis method we are developing could be used militarily. We visualize such AUVs making clandestine surveys of littoral areas. The method of extracting information on water motion from vehicle motion would have application in determining the wave energy in areas of planned amphibious assault. The technique may also find application as a non-acoustic detection and tracking tool. This would find application in "smart" and acoustically quiet weapons that could detect the wakes of vessels and follow them. Torpedoes using the technique in real time could conceivably follow turbulent ship wakes to their targets.

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